Radio Mode Outbursts in Giant Elliptical Galaxies

Paul Nulsen[*], Christine Jones[*], William Forman[*], Eugene Churazov[†,**],
Brian McNamara[‡,§], Laurence David[*] and Stephen Murray[*]

[*]*Harvard-Smithsonian Center for Astrophysics, 60 Garden St, Cambridge, MA 02138, USA*
[†]*Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, 85741 Garching, Germany*
[**]*Space Research Institute (IKI), Profsoyuznaya 84/32, Moscow 117810, Russia*
[‡]*Department of Physics and Astronomy, University of Waterloo, 200 University Avenue West,
Waterloo, Ontario, N2L 3G1, Canada*
[§]*Perimeter Institute for Theoretical Physics, 31 Caroline St. N., Waterloo, Ontario, N2L 2Y5,
Canada*

Abstract. Outbursts from active galactic nuclei (AGN) affect the hot atmospheres of isolated giant elliptical galaxies (gE's), as well as those in groups and clusters of galaxies. *Chandra* observations of a sample of nearby gE's show that the average power of AGN outbursts is sufficient to stop their hot atmospheres from cooling and forming stars, consistent with radio mode feedback models. The outbursts are intermittent, with duty cycles that increases with size.

INTRODUCTION

Chandra X-ray observations have shown that energies deposited by AGN outbursts at the centers of clusters and groups of galaxies are about sufficient to prevent the hot gas there from cooling, consistent with models in which "radio mode" AGN feedback limits cooling and star formation [*e.g.*, 1, 2, 3, 4]. There is similar evidence of AGN feedback in galaxy groups and isolated elliptical galaxies [*e.g.*, 5, 6, 7]. The lack of outbursts in some clusters with short central cooling times [*e.g.*, 8] implies that outbursts are intermittent. Moderately strong shocks [*e.g.*, 9, 10, 7] require large, sustained increases in AGN power, also supporting intermittency.

The long timescales of AGN outbursts (> Myr) permit us only a single snapshot of them. Thus, to study the cycles of intermittent AGN outbursts, we must resort to samples. Here, we present results of *Chandra* observations of a sample of nearby giant elliptical galaxies (gE's).

OUTBURSTS IN THE ELLIPTICAL GALAXY SAMPLE

Based on the samples of Beuing *et al.* [11] and O'Sullivan *et al.* [12], Jones *et al.* (in prep.) have assembled a sample of $\simeq 160$ nearby gE's with $L_K > 10^{10}$ L$_\odot$ that have been observed with *Chandra*. After removal of point sources, including a component due to unresolved point sources [13], 104 of these galaxies show emission from diffuse
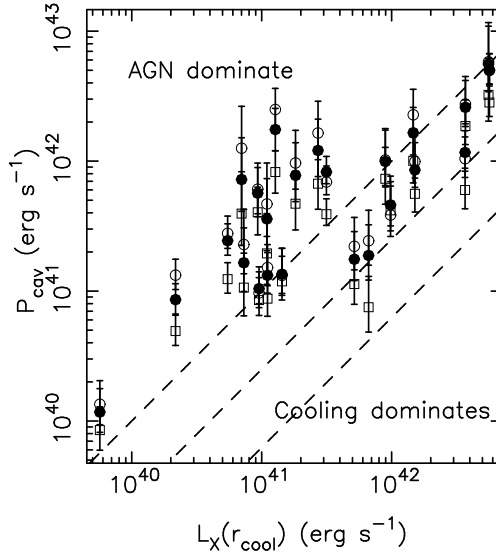
FIGURE 1. Cavity power *vs* cooling power for outbursts in the gE sample. Filled markers, open circles and open squares show P_{sonic}, P_{buoy} and P_{refill}, respectively, with 90% confidence ranges. Dashed lines show $P_{\text{cav}} = L_{\text{X,cool}}$ for energy inputs of $1pV$, $4pV$ and $16pV$ per cavity, respectively, top to bottom.

hot gas. They constitute our sample of gE's with significant hot atmospheres, and 24 of them show cavities due to AGN outbursts.

Many *Chandra* exposures used here are shallow, so that some outbursts are likely to have been missed. In some known radio sources, the detected X-ray cavities are much smaller than the radio source, likely causing their outburst energies to be underestimated. Nor is the *Chandra* archive a well controlled, complete sample. We estimate that roughly 1/3 of nearby gE's have been observed with *Chandra*. However, many nearby gE's that were detected by *ROSAT* have been observed with *Chandra*. Thus, while the sample is incomplete, it is probably representative of nearby, X-ray bright gE's.

Outburst (cavity) powers were determined as in [1, 3]. The energy of each cavity is taken to be the product of its pressure, p, and its volume, V (*i.e.*, $1pV$ of energy per cavity). Three age estimates are used, the sound crossing time, t_{sonic}, the buoyant crossing time, t_{buoy} and the refill time, t_{refill}, providing a guide to the systematic uncertainty in the age estimates [1]. These give three estimates of the mean power, pV/t, for an outburst, P_{sonic}, P_{buoy} and P_{refill}. The cooling power is determined for each atmosphere as the power it radiates from within the region where the gas cooling time is shorter than 7.7 Gyr (look back time to $z = 1$). Cavity power estimates are plotted against cooling powers in Fig. 1. Dashed lines show where cavity power equals cooling power for energy inputs of $1pV$, $4pV$ and $16pV$ per cavity. At $4pV$ per cavity, $P_{\text{sonic}} > L_{\text{X,cool}}$ for every outburst in the sample. In marked contrast, outburst powers scatter about cooling powers for rich clusters [3].

Outbursts are detected in $\sim 1/4$ of the gE sample [*cf.* $\sim 2/3$ of rich clusters, 2]. To study the impact of intermittent outbursts on gE's, we assume that our sample is representative of randomly selected stages of the AGN outburst cycle. Totals of the cavity power estimates are $P_{\text{tot,sonic}} = 2.6 \times 10^{43}$ erg s^{-1}, $P_{\text{tot,buoy}} = 2.9 \times 10^{43}$ erg s^{-1}
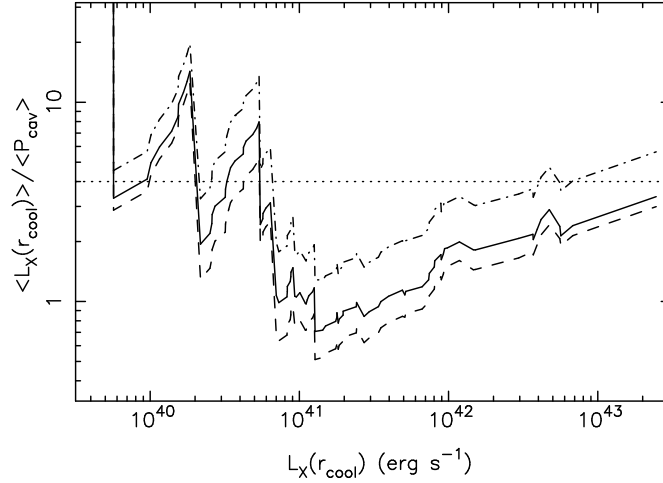
FIGURE 2. Ratio of cumulative average cooling power to cumulative average outburst power *vs* cooling power. The full, dashed and dot-dashed lines show results for P_{sonic}, P_{buoy} and P_{refill}, respectively.

and $P_{tot,refill} = 1.5 \times 10^{43}$ erg s^{-1}, while the total cooling power for all 104 gE's is $L_{tot,cool} = 8.7 \times 10^{43}$ erg s^{-1}. Thus, the ratio of the average cooling power to the average outburst power for the sample is $\langle L_{X,cool} \rangle / \langle P_{cav} \rangle = 3.4$, 3.0 and 5.6, for the three power estimates, respectively.

The minimum energy needed to make a cavity is its thermal energy plus the work required to inflate it, *i.e.*, its enthalpy. For a cavity (radio lobe) dominated by relativistic gas, this is $4pV$. Additional energy is lost driving shocks or sound waves [9, 10] adiabatic losses, leakage of cosmic rays, *etc*. Since cavity powers are also likely to be underestimated, the means of $\langle L_{X,cool} \rangle / \langle P_{cav} \rangle$ above (for $1pV$ per cavity) show that an energy input of $4pV$ per cavity is probably sufficient for the time averaged outburst power to match the cooling power for this sample. Thus, AGN feedback can regulate cooling and star formation in these lower mass systems, as well as in clusters.

As powerful systems dominate these averages, we apply a further check for the fainter gE's. After sorting by $L_{X,cool}$, ratios of the cumulative cooling power to the cumulative outburst powers are plotted in Fig. 2. At small cooling powers, small numbers (and intermittency) make the results very noisy. Nevertheless, the average ratio is consistent with a value of ~ 4 across the whole sample. Thus, intermittent AGN outbursts that deposit $4pV$ per cavity can regulate cooling in all gE's with significant hot atmospheres.

OUTBURST DUTY CYCLE

The cumulative fraction of gE's with outbursts, plotted against $L_{X,cool}$ in Fig. 3, increases with $L_{X,cool}$. If outburst probability (*i.e.*, duty cycle), $p(L_{X,cool})$, is linear in $\log(L_{X,cool})$, a maximum likelihood fit gives $p = 0.09$ at $L_{X,cool} = 10^{40}$ erg s^{-1} and $p = 0.49$ at 10^{43} erg s^{-1}. The fit is just inconsistent with a constant duty cycle at the 90% confidence level. Extrapolating to $L_{X,cool} \simeq 10^{44.5}$ erg s^{-1} gives $p \simeq 0.7$, consistent with results for rich clusters [2]. At 0.23, the overall fraction of outbursts in our sample is also
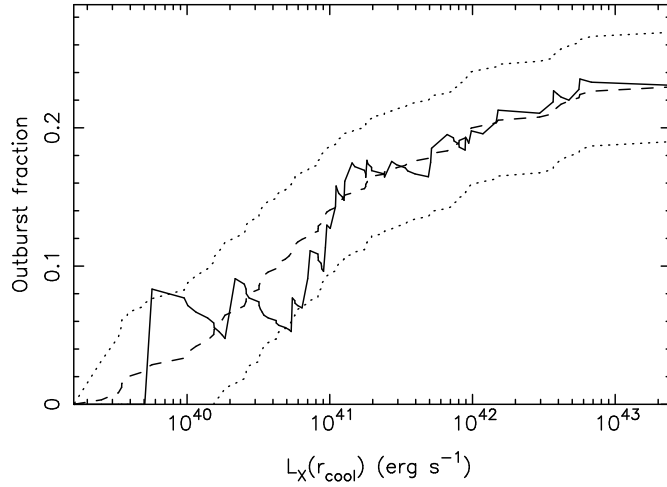
FIGURE 3. Cumulative outburst fraction *vs* cooling power for the sample (full line). The expected value for the best fitting model for this sample (dashed) and its one sigma range (dotted) are also shown.

inconsistent with rich clusters, unless the duty cycle increases with $L_{X,cool}$. Lastly, the smaller duty cycle in smaller systems requires outbursts to have larger powers relative to $L_{X,cool}$ if average outburst power is to match the cooling power. This is seen in Fig. 1, where the trend of the data points is flatter than the dashed lines.

In summary, AGN outbursts can limit cooling in the entire range of gE's with significant hot atmospheres. The outbursts are intermittent, with duty cycles that increase with cooling luminosity.

ACKNOWLEDGMENTS

REFERENCES

1. L. Bîrzan, D. A. Rafferty, B. R. McNamara, M. W. Wise, and P. E. J. Nulsen, *ApJ* **607**, 800–809 (2004).
2. R. J. H. Dunn, and A. C. Fabian, *MNRAS* **373**, 959–971 (2006).
3. D. A. Rafferty, B. R. McNamara, P. E. J. Nulsen, and M. W. Wise, *ApJ* **652**, 216–231 (2006).
4. B. R. McNamara, and P. E. J. Nulsen, *ARAA* **45**, 117–175 (2007).
5. A. Finoguenov, and C. Jones, *ApJ* **547**, L107–L110 (2001).
6. C. Jones, W. Forman, A. Vikhlinin, M. Markevitch, L. David, A. Warmflash, S. Murray, and P. E. J. Nulsen, *ApJ* **567**, L115–L118 (2002).
7. M. Machacek, P. E. J. Nulsen, C. Jones, and W. R. Forman, *ApJ* **648**, 947–955 (2006).
8. M. W. Wise, B. R. McNamara, and S. S. Murray, *ApJ* **601**, 184–196 (2004).
9. D. A. Smith, A. S. Wilson, K. A. Arnaud, Y. Terashima, and A. J. Young, *ApJ* **565**, 195–207 (2002).
10. B. R. McNamara, P. E. J. Nulsen, M. W. Wise, D. A. Rafferty, C. Carilli, C. L. Sarazin, and E. L. Blanton, *Nature* **433**, 45–47 (2005).
11. J. Beuing, S. Dobereiner, H. Bohringer, and R. Bender, *MNRAS* **302**, 209–221 (1999).
12. E. O'Sullivan, T. J. Ponman, and R. S. Collins, *MNRAS* **340**, 1375–1399 (2003).
13. M. Revnivtsev, E. Churazov, S. Sazonov, W. Forman, and C. Jones, *AA* **473**, 783–789 (2007).